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ANALYSIS OF THE POSSIBLE USE OF WIND POWER IN SWEDEN
Part 1
WIND POWER RESOURCES, THEORY OF WIND-POWER MACHINES, PRELIMINARY MODEL 1 AND 10 MW WIND GENERATORS

Bengt Södergård

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16. Abstract

This report deals with several of the aspects that must be considered in respect to the possible use of wind power in Sweden, such as availability and nature of wind resources, cost of this type of energy, etc. There are also sections on the basic theory of calculating the power of wind-power machines, with many tables and diagrams. An appendix gives data for several large wind-power machines constructed in the USA, Great Britain, etc. The conclusion is reached that the use of wind power in Sweden is not feasible, primarily because of its high cost per kWh.

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Aa. Wind Velocity and Duration /2*

The highest average wind velocity in Sweden is measured at coastal stations around the coast from Uddevalla-Skåne to the coast of North Uppland. The reason that the coastal areas have higher average wind velocities than the inland areas depends on the fact that the friction of air masses against the water is lower than that against hilly land with trees, houses, forests, etc. Sea breezes and land breezes contribute to the yearly average value of the wind velocity at the coastal areas.

The northern part of Bohuskusten has a slightly lower average wind velocity than the southern coast. We believe this depends on the fact that this part of the coast is situated on the lee side, behind the steep part of southern Norway, with NW and N winds. The coast of Norrland has a lower average wind velocity than the coastal areas south of it, which can probably be explained by the fact that, in general, W-E low pressure masses pass Sweden more often on a latitude that favors high wind velocity in southern Sweden. It can be explained further that wind coverage of the land masses is on an average wider than on the ooast of Norrland. The westerly winds are also subdued by the Scandinavian mountain range.

High wind force is measured in local mountain regions: however, in very hilly terrain, the wind's force and direction depend to a large degree upon the formation of the terrain. Altitudes lower than the mountain tops are most often on the lee

*Numbers in the margin indicate pagination in the foreign text.

side. This makes it very difficult to find suitable sites for constructing wind-power machines besides mountain tops. The search for suitable sites has led us to the conclusion that it is better to find a flat area at a lower altitude a considerable distance away from the mountain tops. Hardangervidda, Norway, is just one such place, and it ought to be most suitable for wind-power machines.

There is an objection to erecting many wind-power machines, placed in groups of hundreds, because of the loss of aesthetic value. This argument is even stronger if the construction of wind-power machines is placed in a very densely populated or recreational area, rather than in a sparsely populated area. There is no doubt that the most attractive sites for wind-power machines are on the coastal islands and at the coastlines up to 30 km inland. Because of this argument, it would be wise to investigate whether wind force is ample on the sparsely populated highlands of southern Sweden. It is well-known that this higher friction exists at hilly areas with vegetation in comparison with friction at the surface /3
of wave-building water, which does not subdue the force of the wind that much. But in the inland area, the contribution of the sea breeze to the average yearly wind velocity is lost. It appears mostly during the summer, when the need for electrical energy is less. Therefore, the loss is moderate. The higher cost of the height of the hub on the machine (higher mast or tower) should bring the average wind velocity on the southern Swedish highlands up to the acceptable level set for the coastal areas.

The use of a wind velocity duration curve for the site of the installation or of a representative measuring station nearby is the basis for calculating the amount of energy a wind-power machine can produce during a year. The duration curve consists of wind-velocity observations arranged in order during a time period: monthly, yearly, or 10-yearly. The duration curve can be used as the time integral of the wind velocity distribution function for the same period of time.

The preliminary basis for judging wind resources in the south of Sweden is accounted for by duration curves which have been calculated on the basis of data from four meteorological stations. These data are found in the following tables and diagrams. Guided by these duration curves, I have given data for a duration curve with wind velocity somewhat less than that observed from the two highest points at Hanö and Landsort. This is the duration curve for coastal sites at an altitude of 50 m above sea level or the mainland. This duration curve is recommended as a preliminary reference curve. A dependable basis for judging wind resources is obtained through the use of an anemometer (wind measuring device) located at the height of the hub of the wind-power machine at the proposed construction site. Measuring can be carried out during a relatively short period, as, for example, during a 6-month winter period. A reliable average for a longer period of time is obtained through correcting the relationship between the average wind velocity measured at nearby weather stations, partly for the same short period and partly for the 10-year period. Two weather stations with the same average wind velocity for a long time period have, according to our experience, almost identical duration curves. It follows, then, that if one has established a certain value of the average wind velocity from one measuring site, through the above-mentioned method, then one can also obtain a certain value in the form of the duration curve by taking a reading from a weather station with the same average wind velocity over a long time period.

The wind duration at four observation sites.

Wind Duration

Measuring Sites	Duration of the Wind, Yearly % of Wind Velocity, m/s 0–2	3–5	6–8	9–11	12–14	15–17	18–20	21–29
North point of Öland; average measurement value 1961–1968. Measuring height 35 m above sea level. SMHI data	100	89.1	57.4	26.9	9.2	2.6	0.7	0.24
Landsort. Estimate, acc. to data from [6, p. 15]. Ten years of measurements. Measuring height	100	89.6	71.7	48.8	27.9	13.0	5.9	1.9
Torslanda. Estimated using SMHI statistical data. Years 1961–1970. Measuring height 10 m above land	100	88.0	55.3	25.6	9.1	2.5	0.7	0.1
Hanö. Estimated from old, handwritten protocol from SMHI. 10794 observations during 10 years. Measuring height 72 m above sea level, 17 m above land	100	90.9	71.3	47.1	27.1	13.8	6.2	1.7
Proposed reference data for wind duration at a height of 50 m over free plains	100	90	71	45	24	11	4	1

At Torslanda, measurements have been taken at a lower altitude over the surrounding area, besides the above-mentioned measurements. The wind force increases with the height above ground. After recalculating with a factor of 1.25 for data from Torslanda, the measurements reach almost the same wind velocity value as those of Landsort and Hanö. The factor 1.25 has been estimated using the following equation:

$$v_{50} = v_{10} \cdot (50/10)^{0.14}$$

Please refer to the section headed "Wind profile."

The reference curve proposed coincides with the corrected height curve for Torslanda. I estimate that there are many sites suitable for the construction of wind-power machines which have this value or better. The actual measurement values from Hanö and Landsort are higher than the proposed values of the reference curve.

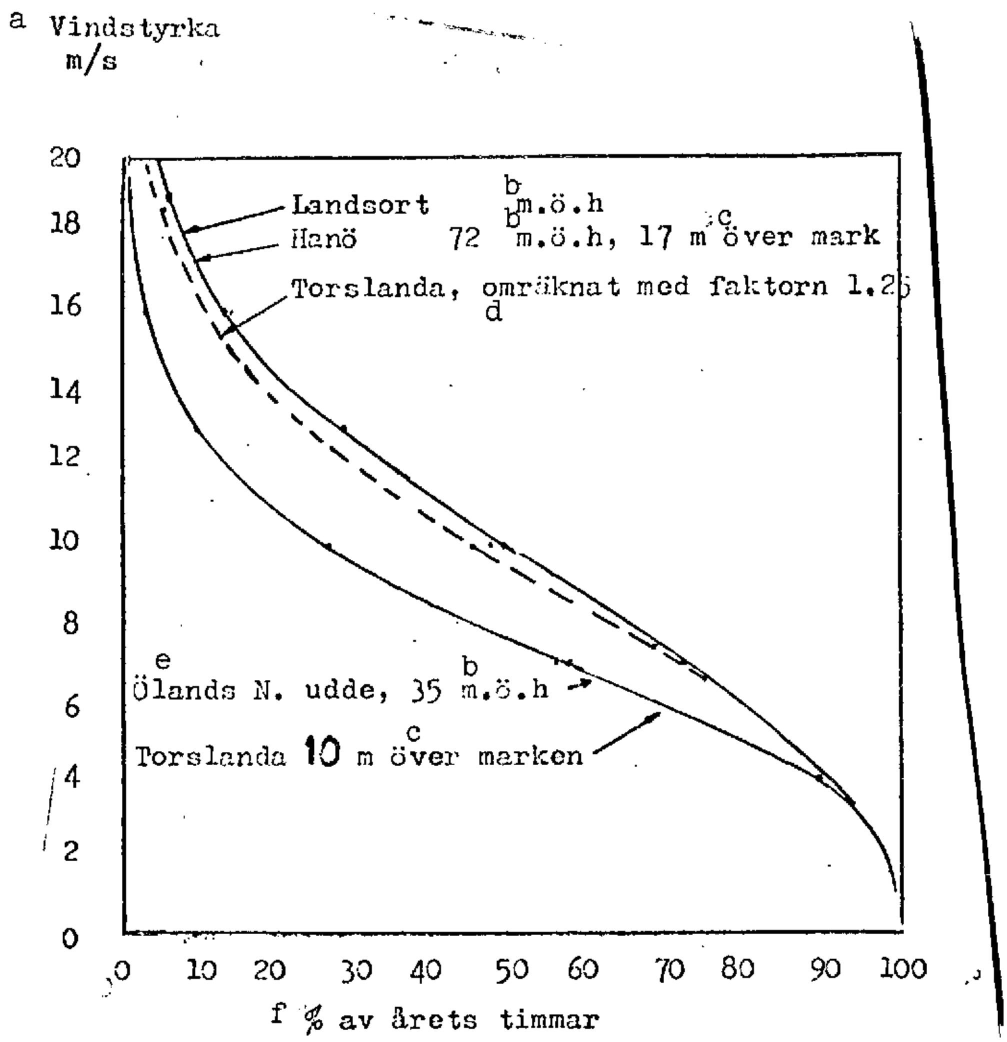
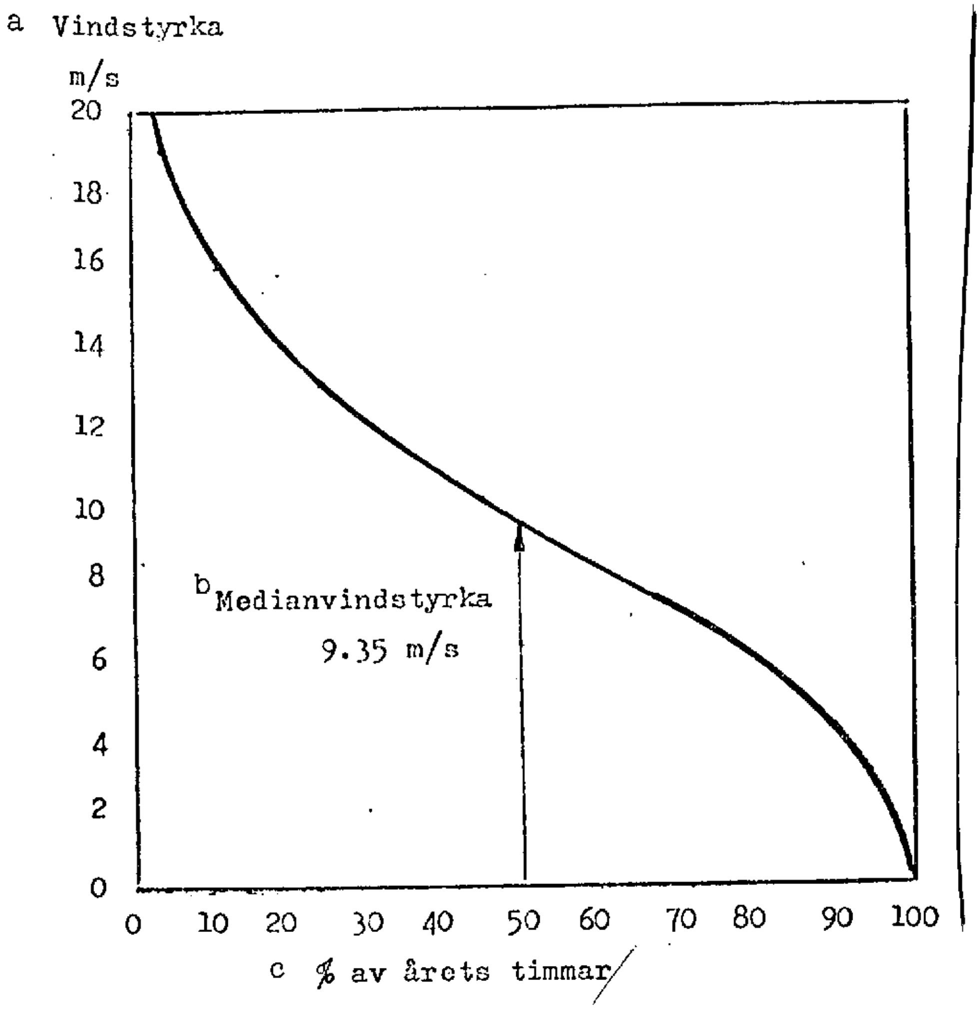


Diagram 1. The wind duration at four observation sites.

Key: a. Wind velocity
b. Meters above sea level
c. Meters above land
d. Conversion factor 1.25
d. North point of Oland
f. % year-hours



Preliminary reference curve for wind duration taken from open sites at a height of 50 m above ground in the south of Sweden.

Key: a. Wind velocity
b. Average wind velocity
c. % year-hours

Ab. Seasonal Distribution of Wind Resources

The average wind force for the fall and winter months is higher than that for the year as a whole. This favors electricity production by the use of wind-power machines, since the need for electrical energy is greatest during the same time that the wind is at its strongest. Electrical energy from the wind-power machines is on the whole proportional to the cube of the average wind velocity v^3. The ratio of the cubes of two wind velocities is greater than the ratio of the same wind velocities. This means that electricity production of the wind-power machine for 1 year becomes greater in the fall and winter months as compared to the ratio between wind force for a windy month and the yearly range of the wind force.

As a basis for estimating seasonal wind energy, I have used the wind observations from the weather station at the north point of Öland during the years 1961-1968.

The estimate was carried out according to the following data:
Average wind velocity for the year estimated at 7.75 m/s
Estimated average wind velocity for each month, v_{month}, is found in the table below.
The cube of the ratio $v_{month}/7.75$ is a measure of the accessible wind energy and has been drawn up in the following diagram, which shows how the wind energy is distributed during the year.

Month	Average Wind Velocity, m/s	Average Wind Force Ratio	$(v_{month}/7.75)^3$
Jan	8.77	1.13	1.44
Feb	8.47	1.09	1.30
Mar	8.32	1.074	1.24
Apr	7.38	0.953	0.87
May	6.85	0.873	0.66
Jun	6.86	0.872	0.66
Jul	6.43	0.830	0.57
Aug	6.88	0.887	0.70
Sep	6.85	0.873	0.67
Oct	8.20	1.056	1.18
Nov	8.83	1.140	1.48
Dec	8.86	1.144	1.50

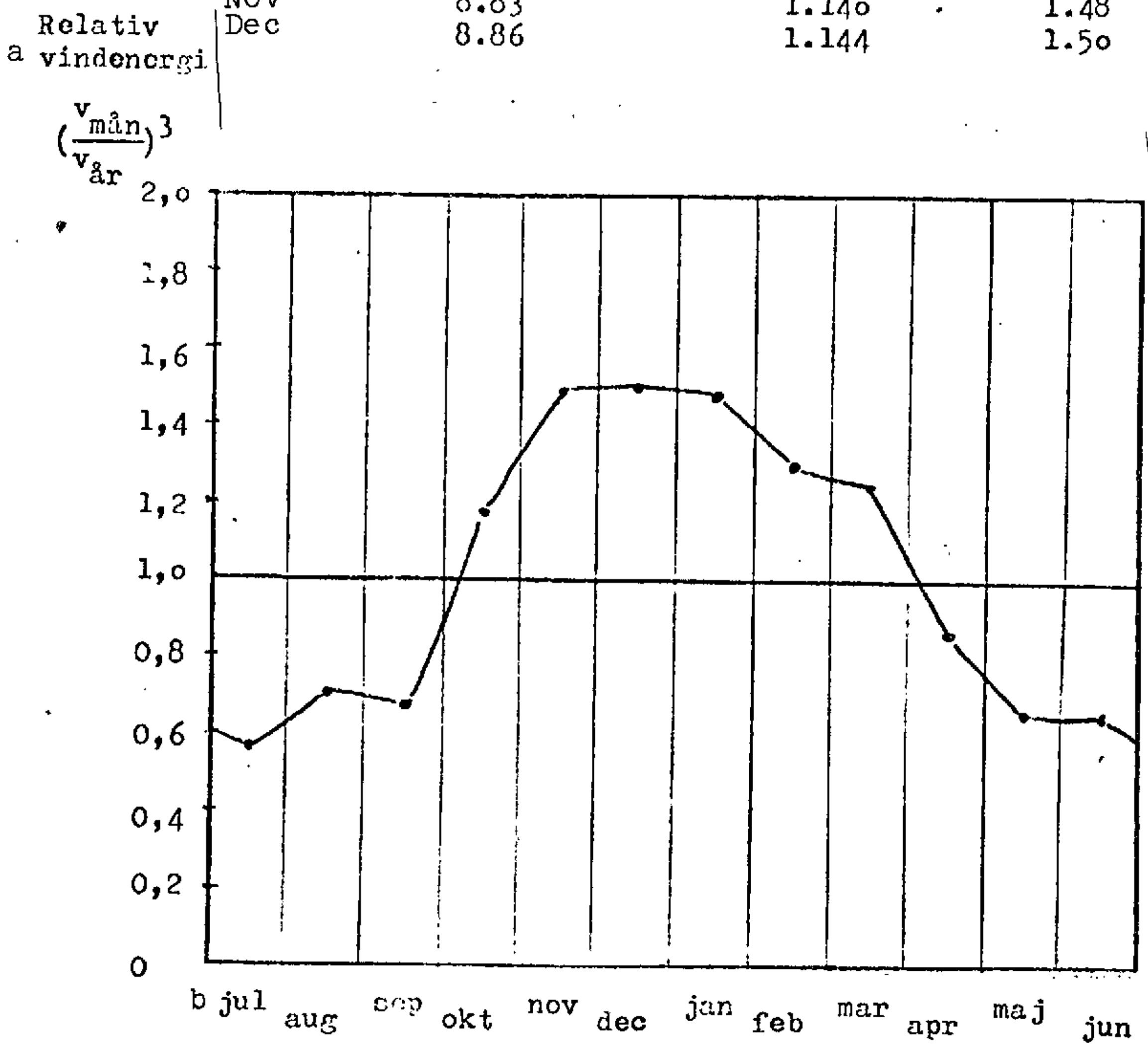


Diagram 3. Seasonal distribution of wind energy.

Key: a. Wind energy ratio $(v_{month}/v_{year})^3$
b. Jul = July (typ.)

Ac. Increase in Wind Force Due to Height above Ground /9

The increase in wind force due to height above ground is also called the "vertical gradient of the wind force," and the "wind profile."

The theory of wind conditions in the layers of air near the ground, i.e. from the ground up to approximately 200 m in height, is very well dealt with in O.G. Sutton's book entitled Atmospheric turbulence [2]. The book also cites some figures as a basis for the wind profile. In the Russian book entitled Investigation of the Bottom 300-Meter Layer of the Atmosphere are found theories of the wind profile and quite a few measurement data reported in the form of diagrams. Neither of these books, however, is directed toward the needs of the designer of wind-power machines. On the other hand, the designer will find help in E.W. Goldings' book, entitled The generation of electricity by wind power [4]. In the chapter called "Wind characteristics and distribution" can be found a careful and easily surveyed report on work accomplished during 1940-1954 in Great Britain, the U.S., Denmark, West Germany and France. The section on wind force from Hütte, Maschinenbau is also a very good source of information on the wind profile. Many data are also to be found on wind resources from Putnam's book entitled Power from the wind [5]. The above-mentioned books are the principal sources on which the following summary of the wind profile is based.

By measurement of wind velocity with several wind-speed anemometers at various heights from a high mast or a similar device, it has been established that the resultant distribution obtained is great. It is important to keep in mind that, when one speaks of the wind profile, it becomes a question of a statistical mean value derived from a number of measurements. An occasional deviation from the mean value can, at times, be very great. A compilation of the results from a number of measurements and a proposal for reference data on the wind profile are shown in a table below.

The coefficient of dynamic viscosity of the air has a relatively low value. This means that if one assumes that the flowing air is laminar, one could find high wind speeds a few meters above the tops of sparsely growing trees, but a few meters lower, there would be no wind at all. During the 6 winter months, the air layers closest to the ground are often colder than the air at a height of 50 m. This depends upon radiation gain of the air, ground, and the Earth's atmosphere. The cold air layers from the ground are then stable and still, and higher air layers can glide above them with considerable speed, up to about 15 m/s. However, at higher speeds than that, in air layers above 50 m in height, a turbulent agitation begins due to natural obstacles. /10 The areas of turbulence increase due to natural obstacles which cause the stable air layers on the ground to break up. We then have gusty ground wind. The fall in the wind profile is therefore to a great extent dependent upon the degree of turbulence in the air layer at the ground. With a high degree of turbulence, the pulse exchange between ground air and air in the higher stratum becomes great. This corresponds to a relatively high power, up to about 0.80 in the power function of the wind profile. The degree of turbulence depends in the first place upon the air temperature drop measured at different heights above ground. A synonymous expression is the "vertical temperature gradient of the air." To balance the radiation gain (air, ground, atmosphere), the gradient is determined by the adiabatic temperature drop caused by the air pressure decrease due to height. This temperature gradient appears in cloudy weather and is close to the statistical mean drop in temperature gradient. The adiabatic temperature drop is equivalent to a power of about 0.14; in other words, that power which was proposed as the norm in the wind profile function.

The effect of different degrees of friction on the ground does not seem terribly important, judging from measurements taken over grassy plains in comparison with those taken over tree tops in a forest.

Large obstacles in the terrain, such as steep mountain ranges or high buildings on flat ground, can have a considerable effect on the wind velocity in the area. On the crown of gently sloping hills, we find a greater wind force than in the same plane above surrounding flat ground. This effect ought to be observed when picking an inland site for wind-power machines. The highlands of southern Sweden have such formations and are suitable for the construction of many wind-power machines on the same plateau. As one might expect, this effect is very important on the coastal islands. This means that the same yearly energy from the wind-power machine can be obtained by using a lower hub height, such as a lower tower or mast, than is used at other sites.

Measurements and reports of the wind profile drop for heights over approximately 200 m are less extensive, and they are conflicting. Both theory and measurements give a certain proof that the principal pulse gain takes place within the height range of 0-200 m. Above that height, the wind force increases at a slower rate than the normal curve of the wind profile indicates. This is the reason for setting the values for greater heights in parentheses in the table of wind profile data.

Increase in wind force due to height above ground: A survey /11

Source	Height above flat ground or surface of water, m 5	10	20	50	100	200	500
Reference curve proposed by B. Södergård, according to the equation $v_H = v_h \cdot (H/h)^{0.14}$ Reference height h = 10	0.91	1	1.10	1.25	1.38	1.52	(1.73)
According to Hütte, Maschinenbau [8], based on data from five reports	0.91	1	1.09	1.26	1.40	1.64	(1.84)
Equation for limited stratum for measuring in a wind tunnel. Flat surface and relatively high Reynolds number $v = v_1(z/z_1)^{1/7}$		1	1.10	1.26	1.39	1.53	(1.75)
Measurements over tree-covered ridges in New England. h = 0 by height of tree tops. Data from [5, Fig. 40]	0.91	1	1.10	1.21			
According to measurements by J. Juul, Denmark, given again in [4, p. 82 and Fig. 30]. Measurement over cultivated land with trees and houses nearby	0.81	1	1.33	1.64			
Measurements at Costa Hill, Orkney. According to [4, Fig. 31b]. 150 m above sea level. Ground sloping approximately 1:5	0.93	1	1.07	1.13			
Measurements at Grandpa's Knob, Vermont, USA [5]	0.94	1	1.17	1.26			

The value of the wind force, as reported by the weather stations (as a rule, every 6 hours), is the mean value during a 10-minute measuring period. Sometimes the wind has hardly any deviation from this mean value, but under certain weather conditions, especially in conjunction with clouds, large and rapid changes in wind velocity can take place: the wind is gusty. In second-long bursts, the wind velocity can become 50% higher than the mean wind speed. For example, 20 m/s with gusts up to 30 m/s (see [6]).

The production capacity of the wind-power machine is proportional to the cube of the velocity, v^3. During gusty winds, the total production becomes $v^3 \cdot \Delta t$ greater than $(v_{mean})^3 \cdot t$ during time t = the sum Δt. Consequently, it follows that gusty wind supplies more useful energy to the wind-power machine than has been calculated by standard wind observations. From this one can consider calculating the gust efficiency factor by the following integral:

$$\text{Gust efficiency factor} \quad e_{gust} = \frac{\int_0^T v^3 \cdot dt}{T\left[\frac{1}{T}\int_0^T v \cdot dt\right]^3}$$

This factor is used to revise the v^3 curve calculated from the data in standard wind observations of 10-minutes measuring time. In book [4, Table 111, p. 32] is found a compilation of measurement results for determining the value of this efficiency factor. An applicable value seems to be $e_{gust} = 1.01$.

A presupposition for the wind-power machine to be able to catch and make use of this extra energy increase is that the propeller be constructed with a certain margin in the form of the available lift coefficient for the propeller blade profile (vertical section). If the lift capacity is used to the maximum or near maximum by the average wind force prevailing at the time, the result could be an excess release of the normal air current which makes contact with the profile. This means that the extra energy increase is not utilized. This release also has a vibration-inducing effect which can result in the ac generator falling out of phase with the network.

Rapid angle adjustment of the propeller blade increases the machine's capacity to make use of the energy in gusty winds. In addition, if this adjustment is rapid, the propeller blade can be burdened with a higher lift coefficient.

Af. Frequency of Periods with Low Wind Velocity /13

North point of Öland; measuring height 35 m; wind statistics for the 10-year period 1961-1970.

The years 1961-1964: Wind reports three times every 24 hours, at 0700, 1300, and 1900 hours.

The years 1965-1970: Wind reports three times every 24 hours, at 0100, 0700,1300, and 1900 hours.

The periods of lengths 3 to 24 hours or more have been used in the table (nine or more consecutive readings in the years 1961-1964, 12 or more consecutive readings in the years 1965-1970). Only the winter months December, January, and February are used in the table.

Year	7 m/s or less			6 m/s or less		
Year	Date of Beginning of Period	Number of Readings	Period Length, 24 hours	Date of Beginning of Period	Number of Readings	Length of Period
1	2	3	4	5	6	7
1961	4 jan	19	6.35			
	17 jan	17	5.75	19 jan	9	3.o
	31 jan	13	4.3	31 jan	9	3.o
	21 feb	10	3.3	21 feb	10	3.3
1961	dec	--				
1962	jan	--				
1962	27 feb	15	5.o	27 feb	12	4.o
1962	22 dec	10	3.3	22 dec	10	3.3
1963	7 jan	13	4.3			
	22 jan	10	3.3	22 jan	10	3.3
	26 jan	14	4.7	26 jan	12	4.o
	20 feb	15	5.o	20 feb	15	5.o
	25 feb	18	6.o	27 feb	12	4.o
1963	1 dec	17	5.7	1 dec	9	3.o
	9 dec	9	3.o			
1964	5 jan	25	8.3	5 jan	10	3.3
	28 feb	13	4.3	28 feb	13	4.3
1964	25 dec	9	3.o			
1965	22 jan	15	3.75	22 jan	15	3.75
	feb	- -		- - -		
1965	dec	- - -			- - - -	
1966	5 jan	14	3.75	5 jan	13	3.25
	16 jan	12	3.o			
	17 feb	12	3.o			
	21 feb	18	4.5			
1966	5 dec	13	3.25			
	19 dec	16	4.o			
1967	15 jan	12	3.o			
	23 jan	13	3.25			
	9 feb	29	7.25	9 feb	28	7.o
	20 feb	12	3.o			
1967	dec		- - - -			
1968	jan		- - - -			
	feb		- - - -			
1968	12 dec	12	3.o	12 dec	12	3.o
1969	jan		- - - -			
	27 feb	20	5.o	27 feb	20	5.o

 [Continued on following page.]

Table, cont'd:

1	2	3	4	5	6	7
1969 1970 1970	dec 7 jan 19 jan feb	13 17	---- 3.25 4.25 ----	7 jan 19 jan	12 17	3.0 4.25
1970	dec		----			

Note: During the long low-wind-velocity period beginning 9 February 1967, wind velocity was 5 m/s or less during 2.7 days,
4 m/s or less during 1.5 days.

Summary of Weak Wind Statistics

The months December, January, and February are called the winter quarter.

	Number of Periods of Slow Winds During Ten Winter Quarters with Period Length 24 Hours					
	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9
Wind velocity 7 m/s or less	15	7	5	2	1	1
Wind velocity 6 m/s or less	11	5	2	-	1	-

Comments

With wind velocities that vary between 6 and 7 m/s, the wind-power machine that I have constructed will have an estimated 30% of the full effect. It will produce 17% of the full effect when the wind velocity varies between 5 and 6 m/s. Loss of effective supply takes place at a wind velocity of 4.4-4.7 m/s (the exact value can be estimated after closer study of the disposition of starting from a standstill).

It is clear from the above table that during the winter quarters for the 10 years, the wind velocity fell below 6 m/s only once for the duration of a week. Still, a wind-power machine constructed in such a way as to take advantage of weak winds is effective to a certain extent. Therefore, it seems safe, if the energy accumulation is proportional to a week's accumulation of the mean energy from wind-power machines.

Ba. Theory of the Maximum Power from a Wind-Power Machine Propeller/15

For a long time, the theory of pulse exchange between propeller and the flow through the propeller a r e a has been used when calculating thrust in airplane and ship propellers. The problem posed is that of a given axial power designed to produce a maximum thrust in the propeller. The problem is slightly different when the propeller of a wind-power machine is involved. In this regard, the problem is solved by bringing about a maximum power in the propeller shaft by the current accessibility of energy and pulse quantity in the air flowing through it.

This pulse theory was developed by Albert Betz, and it has been useful in calculating the maximum available power of the wind-power machine propeller. It was published in 1927. After my revisions, the deductions are as follows:

The undisturbed wind velocity v in front of the propeller is braked to a lower speed $v\frac{(1+x)}{2}$ by passage over the propeller's rotary plane. A little behind the propeller, the speed has further decreased to $x \cdot v$. Then the power exchange between the propeller and the airflow $\dot{m}$ which is flowing through with propeller area $A = \pi R^2$ has been completed (R = the radius of the propeller). The airflow $\dot{m}$ is the product of area A and velocity $v(1+x)/2$ and the air density ρ, or $\dot{m} = \rho A v(1+x)/2$. The mutual exchange of force F between propeller and airflow in the base calculation of current direction is mechanically $F = d/dt(\dot{m}v) = \dot{m}v(1-x)$. When the airflow emits this power P to the propeller, it is the product of force F and the speed at power alternation. In other words, $\frac{1+x}{2}v$. It follows then, that the power of loss-free energy exchange which can be extracted from the propeller shaft is

$$P = \rho \cdot A \cdot v^3 \left(\frac{1+x}{2}\right)^2 \cdot (1-x)$$

This function reaches its maximum when $x = 1/3$, or when the air behind the propeller has slowed down to a speed one-third of the undisturbed wind speed v in front of the propeller. With the above-mentioned value of x, the maximum theoretical power exchange value becomes $P = \frac{8}{27} \rho A v^3$.

This is the equation presently used in calculating the theoretical maximum power of a wind-power machine propeller. Besides the term "pulse theory," the appellation "beam theory" has also been used, because one counts on interaction between the propeller and the entire airflow (air beam) which passes the propeller area. /16

There are objections: Some critics maintain that an overrating of the available power is implied. Others maintain that it is underrated. See [4, p. 192]. In the operation of wind-power machines, it has been shown that more power is given forth than was estimated. It is not clear whether this can be classified as an underrating in the beam theory equation, or whether this is due to other reasons.

/17

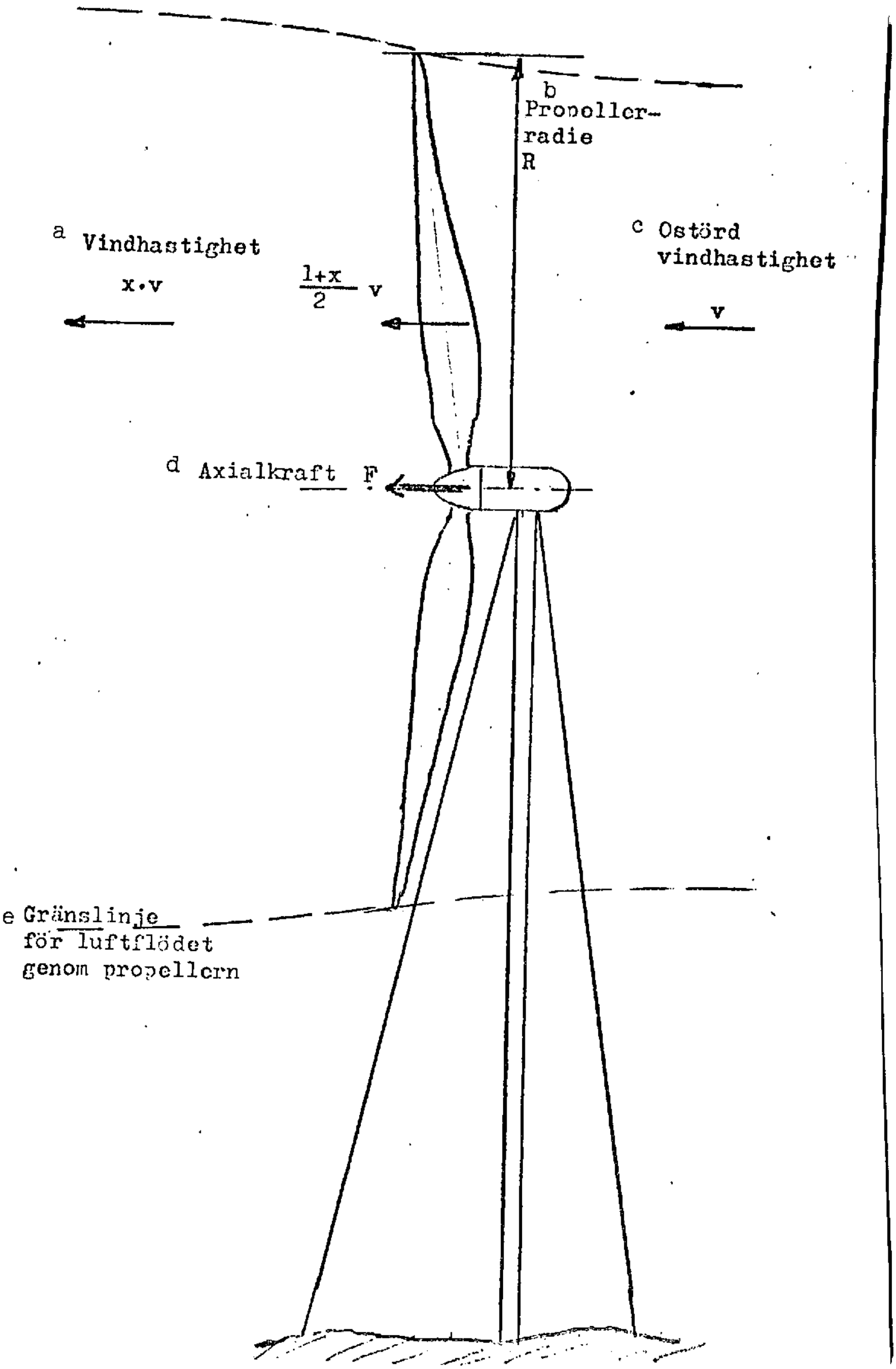


Fig. 1. Decrease in wind passing the propeller.

Key: a. Wind speed; b. propeller radius; c. undisturbed wind speed; d. axial force; e. borderline for airflow through propeller

Bb. Axial Force at the Propeller Axis

/18

The axial force F at the propeller axis or the axial force of the propeller axis is essential in estimating the resistance of propellers, masts, tie ropes, and some other parts. In deducing the maximum theoretical power, we obtain the following term for force:

$$F = \dot{m} \cdot v \cdot (1-x) = \rho \cdot A \cdot v \cdot \frac{1+x}{2} \cdot v \cdot (1-x)$$

With x = 1/3, it becomes

$$F = \frac{4}{9} \cdot \rho \cdot A \cdot v^2$$

This is the maximum axial force of the propeller axis that can be caused by the force of the air. The force F could also be termed a function of power P. The power is the product of the force and velocity at power alternation

$$P = F \cdot \frac{1+x}{2} \cdot v = F \cdot \frac{2}{3} \cdot v$$

from which is obtained $F = \frac{3}{2} \cdot \frac{P}{v}$. This is the force at ideal, loss-free energy conversions between air and propeller. An actual propeller has friction loss. This is taken into consideration in the equation by putting in the aerodynamic efficiency of the propeller η_a. The equation then becomes

$$F = \frac{3}{2} \cdot \frac{P}{v} \cdot \frac{1}{\eta_a}$$

The following conclusions, among others, may be drawn from the equations:

1. The axial force F becomes less when power P is extracted at greater velocity than at smaller velocity.

2. A high aerodynamic efficiency decreases the axial force, and thereby also the force in many other parts of the wind-power machine.

Bc. Efficiency. Power Density

/19

According to Section Ba, the theoretical maximum power of a wind-power machine is

$$P = \frac{8}{27} \cdot \rho \cdot A \cdot v^3$$

The friction loss of airflow against the propeller blades, mechanical storage loss and gear reduction setting, ohmic loss in electrical generators, etc., plus energy consumption of supporting apparatus bring about a smaller supply in electrical power P_e. These include losses in efficiency η. Then $P_e = \eta \cdot P$ = actual electrical power.

Example of efficiency for a wind-power machine with 200 kW generator power and 32-m propeller diameter: The efficiency numbers refer to the best operating point at about 70% generator power.

Aerodynamic efficiency of propeller $\eta_a = 0.88$
Mechanical efficiency, gear reduction setting, storage, $\eta_m = 0.97$
Electrical generator $\eta_e = 0.91$
Supporting apparatus (angular blade servo), etc. $\eta_h = 0.99$
Blade width factor $g = 1.00$
The product of efficiency $\eta = \eta_a \eta_m \eta_e \eta_h g = 0.77$

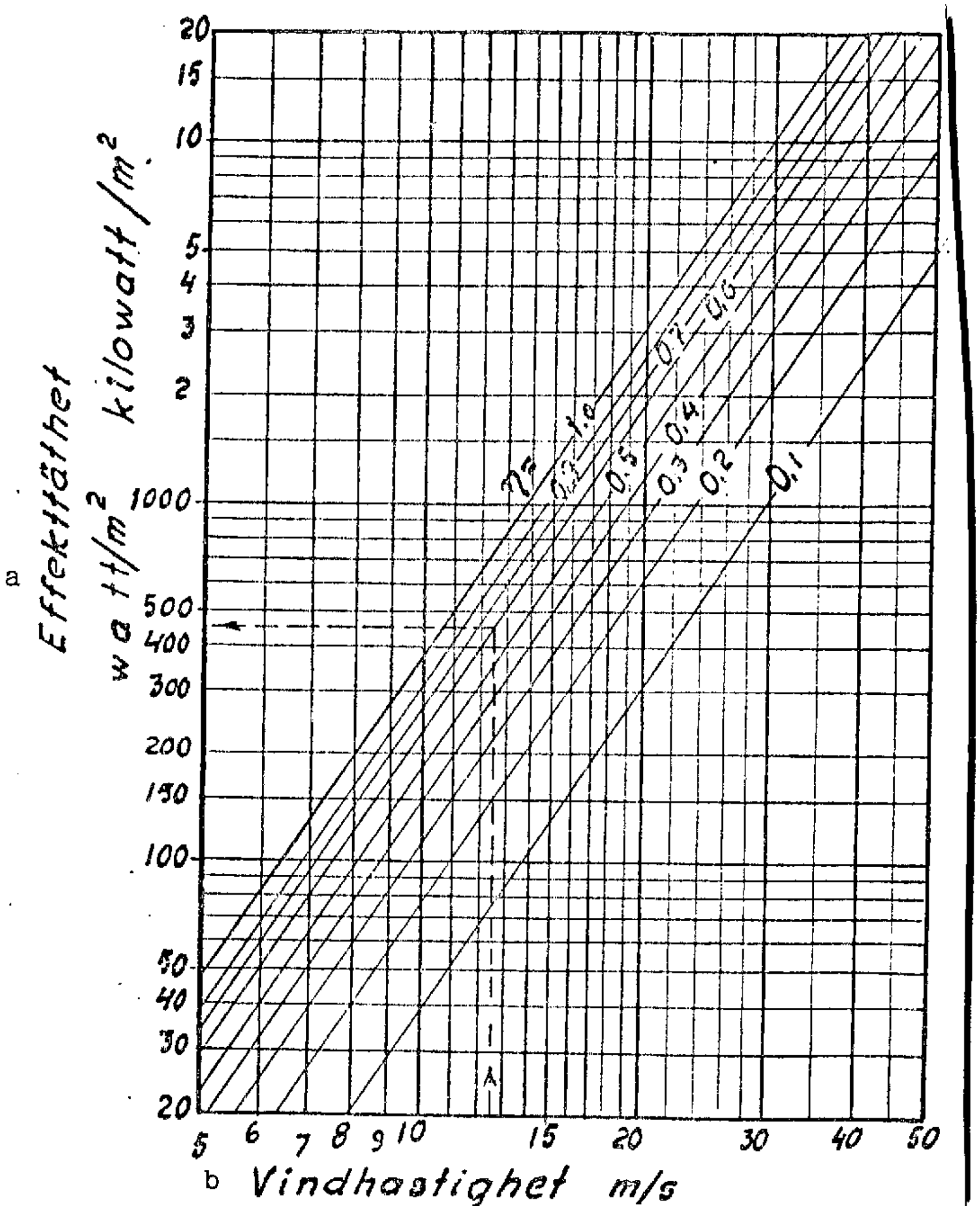
The power density is defined as total output divided by the propeller scanning area, or the circular area $A = \pi R^2$.

$$P_e/A = \frac{8}{27} \cdot \rho \cdot v^3 \cdot \eta \quad = \text{power density, W/m}^2 \text{ or kW/m}^2$$

Power density is a good concept, since wind resources are estimated and compared. In calculations regarding wind-power machines, it is often more flexible to use this power density concept than that of total output. Comparisons in production between different wind-power machines is facilitated with the aid of this concept.

Diagram 4 is a diagram for quick calculation of power density at different wind velocities.

/20



Power density: $P_o/A = \frac{8}{27} \cdot \rho \cdot v^3 \cdot \eta$ $\rho = 1.26\ kg/m^3$

Key: a. Power density
b. Wind velocity

Ca. Dependence of Power Density on Propeller Diameter and Hub Height /21

The power from a large wind-power machine, as compared to a small machine, is greater not just because of the larger propeller area; the increase in wind force due to height is added as well. The increase in wind force due to height takes place relatively more quickly at lower altitudes, which means that the propeller hub height is relatively great for small machines. A suitable standard for hub height in relation to propeller radius is $H = 5R^{0.75}$. This function has been used in calculating the table and diagram below.

The theoretical maximum power for the wind-power machine is:

$$P/A = \frac{8}{27} \cdot \rho \cdot v^3 = \frac{8}{27} \cdot \rho_o \cdot v_o^3 \cdot \left(\frac{v}{v_o}\right)^3 \cdot \frac{\rho}{\rho_o}$$

However, from the power function of the wind profile $v = v_o(H/h_o)^n$ we obtain $(v/v_o)^3 = (H/h_o)^{3n}$. The value of the exponent is $3n = 3 \times 0.14 = 0.42$. With this, the equation for power density can be written

$$P/A = \frac{8}{27} \cdot \rho_o \cdot v_o \cdot (\rho/\rho_o) \cdot (H/h_o)^{0.42}$$

The calculation is carried out using the reference height measurement $h_o = 10$ m; the wind velocity at this height is assumed to be $v_o = 10$ m/s.

The air density is the mean for the year at a height of 100 m above sea level. For each additional 100 m in height, the density decreases by 1.25%. This means a decrease of 2.5% for the largest machine listed in the table, which is relatively unimportant. But the air density has a considerable influence on power loss when wind-power machines are constructed on high terrain, such as the Swedish mountains.

The wind velocity is least in the lower part of the propeller field and increases, according to the power function, to the highest value in the top part of the propeller field. The resultant power density becomes somewhat less than that calculated with wind force at hub height, but the decline is insignificant as a comparative figure, which is the question here. On a machine with 20-m propeller radius, the power is overestimated by 2% due to approximation.

DEPENDENCE OF POWER DENSITY ON PROPELLER AND HUB HEIGHT. /22

R	H	H/h_o	$(\frac{H}{h_o})^{0,42}$	ρ/ρ_o	Relative Power Density	Theoretical Maximum Power Density at v_o=10 m/s watt/m^2	Propeller Area m^2	Theor. Max.; Total Output v_o=10 m/s kilowatt
1	5	0.5	0.75	1.00	0,75	280	3.2	0.9
2	9	0.9	0.95	1.00	0,95	354	12.6	4.5
5	17	1.7	1.25	1.00	1.25	466	78	37
10	28	2.8	1.54	0.999	1.54	575	178	103
20	47	4.7	1.92	0.998	1.91	710	1260	895
50	95	9.5	2.58	0.994	2.56	953	7800	7430
100	160	16	3.20	0.987	3.16	1180	31400	37000
200	270	27	3.97	0.975	3.88	1450	126000	183000

In calculating an actually obtainable power for wind-power machines, use an efficiency of 0.7 at the best wind velocity. Presuppose that this efficiency is at v_o = 10 m/s. The actual power for the above machines then becomes:

Propeller radius, m	1	2	5	10	20	50	100	200
Power, kW	0.6	3.1	26	72	628	5200	26,000	128,000

/27

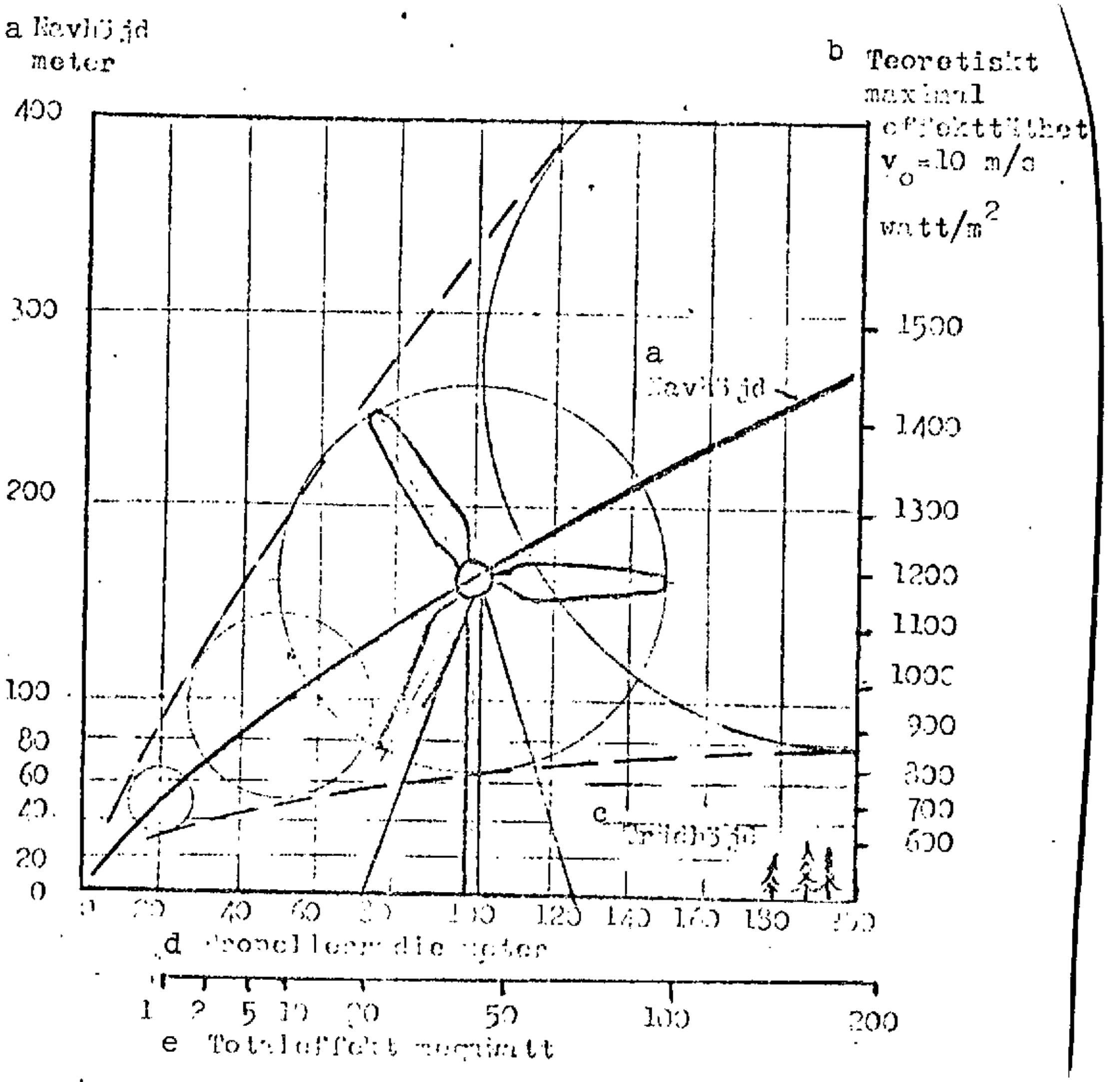


Diagram 4. Total output and power density for wind-power machines of different sizes. The power density is estimated for a 10-m/s wind velocity at 10 m height and theoretical maximum efficiency. Likewise with total output.

Key: a. Hub height
b. Theoretical maximum power density
c. Height of trees
d. Propeller radius
e. Total output

Cb. Calculation of Propeller Diameter and Production of Electrical Energy During 1 Year by Two Wind-Power Machines with Power $P_{10/10} = 1$ MW and $P_{10/10} = 10$ MW

/24

Definition

$P_{10/10}$ = power of wind-power machines at wind velocity 10 m/s and 10 m height.

Thrust

Outside what is clear from the heading, we are assuming that the power limits of the machines are 2 MW and 20 MW. From about 15% power and up to full power at this wind velocity, when the power limit begins, assume the efficiency to be constant at 0.7.

Statement for Calculation

The reference curve of the wind velocity according to Diagram 2 is used as the basis for the calculation. The wind's increase with height above ground is presumed to follow the power function with an exponent 0.14. The connection between propeller diameter 2R and propeller axis height H m above ground is selected according to the relation $H = 5R^{0.75}$. These assumptions are the basis for Diagram 6. In this, we read that the propeller diameters for the two machines ought to be about 48 m and 132 m, if an efficiency of 0.7 is presumed. The mutual relation of the value of the propeller axis height is H = 60 m and H = 115 m. Using these height figures H, the reference duration curve (Diagram 2) is recalculated with the equation $v_H = v_{50}(H/50)^{0.14}$ to obtain a new diagram (Diagram 8), with the wind duration at heights of 10, 60 and 115 m. At the same time, we also calculate the function $v_H^3 = v_{50}^3(H/50)^{0.42}$

Table of Calculations

$(\frac{60}{50})^{0.14} = 1.0258$ $\quad (\frac{115}{50})^{0.14} = 1.1236$

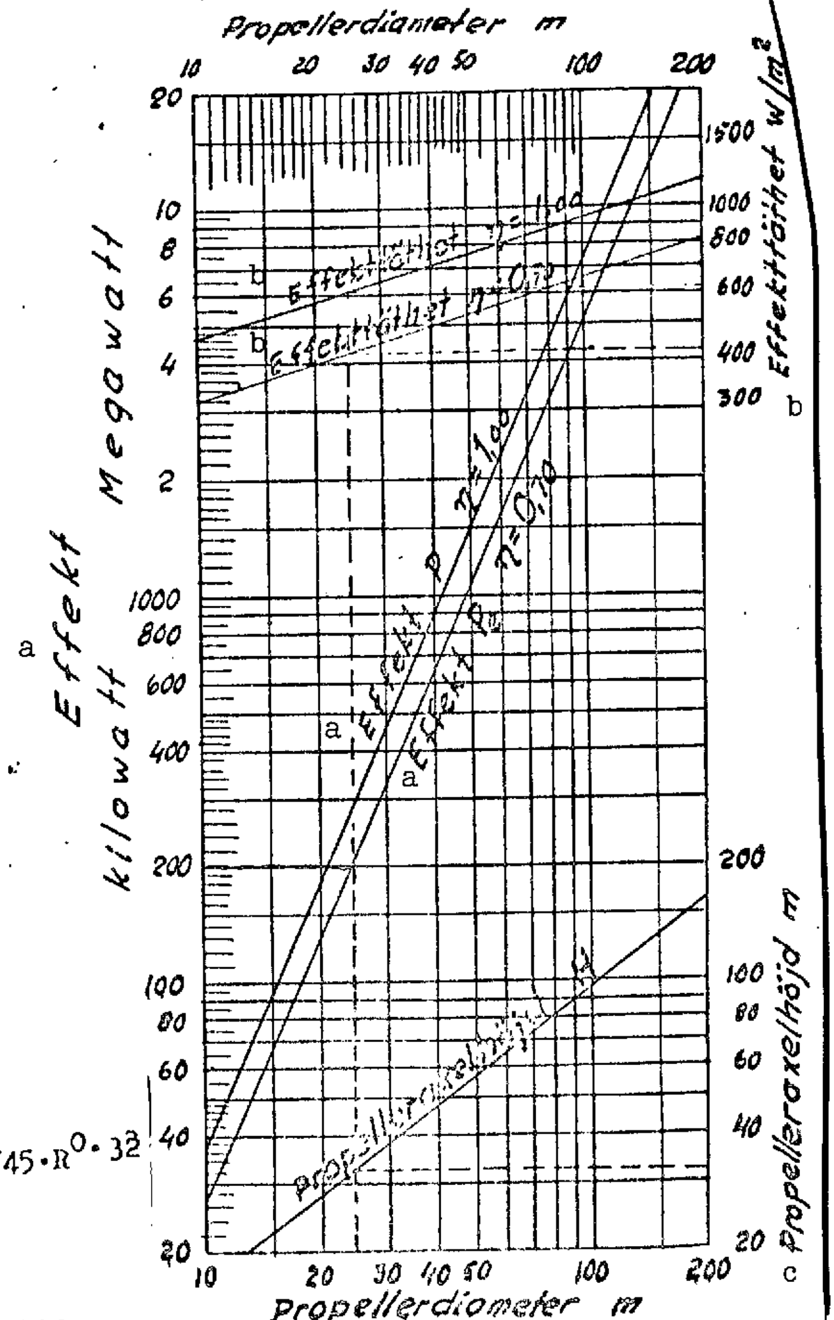
$(\frac{10}{50})^{0.14} = 0.7983$ $\quad (\frac{60}{50})^{0.42} = 1.0735$ $\quad (\frac{115}{50})^{0.42} = 1.418$

Duration	v_{50}	v_{10}	v_{60}	v_{115}	$(v_{60})^3$	$(v_{115})^3$
0.1	16.50	13.2	16.92	18.54	4845	6370
0.2	14.10	11.3	14.47	15.85	3022	3970
0.3	12.10	9.7	12.42	13.60	1915	2518
0.4	10.75	8.6	11.03	12.08	1340	1762
0.5	9.35	7.5	9.59	10.52	885	1162
0.6	8.15	6.5	8.36	9.16	585	768
0.7	7.10	5.7	7.29	7.92	386	508
0.8	5.70	4.5	5.85	6.41	200	262
0.9	3.90	3.1	4.05	4.44	64	84
1.0	0.00	0.0	0.00	0.00	0	0

Diagram 6 (p. 29): The wind-power machine's propeller diameter, hub height, power at efficiencies 1.00 and 0.70; also power density at wind velocity $v = 10$ m/s at a height of 10 m ($v_{10} = 10$). Power and power density at another wind velocity v_{10} is obtained through multiplying the derived power or power density by a factor $(v_{10}/10)^3$ (see attached table).

Key: a. Power
b. Power density
c. Propeller axis height

v_{10} m/s	$\left(\frac{v_{10}}{10}\right)^3$
5	0.125
6	0.216
7	0.343
8	0.512
9	0.729
10	1.000
11	1.331
12	1.728
12,62	2.000
13	2.197
14	2.744
15	3.375
16	4.096
17	4.913
18	5.832
19	6.859
20	8.000



Equations used as the basis for the diagram:

$$\left.\begin{array}{l} v = 10\cdot\left(\frac{H}{10}\right)^{0.14} \\ H = 5\cdot R^{0.75} \end{array}\right\} \quad v^3 = 745\cdot R^{0.32}$$

$$P = \frac{8}{27}\cdot\rho\cdot\pi\cdot R^2\cdot v^3$$

$$\rho = 1.26\ \mathrm{kg/m^3}$$

height 100 m above sea level

$$P = 870\cdot R^{2.32} \qquad P_e = \eta\cdot P$$

Example: What propeller diameter is needed for 200 kW power with a total efficiency of 0.7? Follow the dashed lines in the diagram to diameter 24 m. Power density: 430; Axis height: 32 m.

[Diagram 6. Caption and key on previous page.]

Air density for both machines is calculated as $\rho = 1.26\ kg/m^3$. /27
The cube of the wind velocities is multiplied by $8/27\rho = 0.373$. Thus, the theoretical maximum power density is obtained (see curves in Diagram 9). The solid lines indicate the machine with 1 MW power, $P_{10/10}$, and for the larger machine, the dashed lines are used. Seventy percent of the ordinate of these curves is taken to be equal to the actual electrical energy density P_e/A. Curves for these are also drawn in the diagram. Here it is also assumed that the power is zero at $v_{60} = 5.5$ m/s and $v_{115} = 6$ m/s.

$$\text{With } v_{10} \text{ at } v_{60} = 10 \cdot 6^{0.14} = 12.84$$
$$v_{115} = 10 \cdot 11.5^{0.14} = 14.07$$

One can see from Diagram 8 that these wind speeds occur at the duration 0.28. A vertical line at this duration figure cuts the power density curves with the ordinate 553 W/m^3 (small machine) and 725 W/m^2 (large machine, 10 MWe).

The required propeller areas are carefully calculated with these power density values.

$A = 10^6/553 = 1810\ m^2$ Diameter $2R = 48$ m (1 MW)
$A = 10^7/725 = 13,800\ m^2$ Diameter $2R = 132.5$ m (10 MW)

According to the supposition, the power range will accommodate 2 MWe and 20 MWe. This occurs at double the value of the power densities calculated above; in other words, at $P_e/A = 1106\ W/m^2$

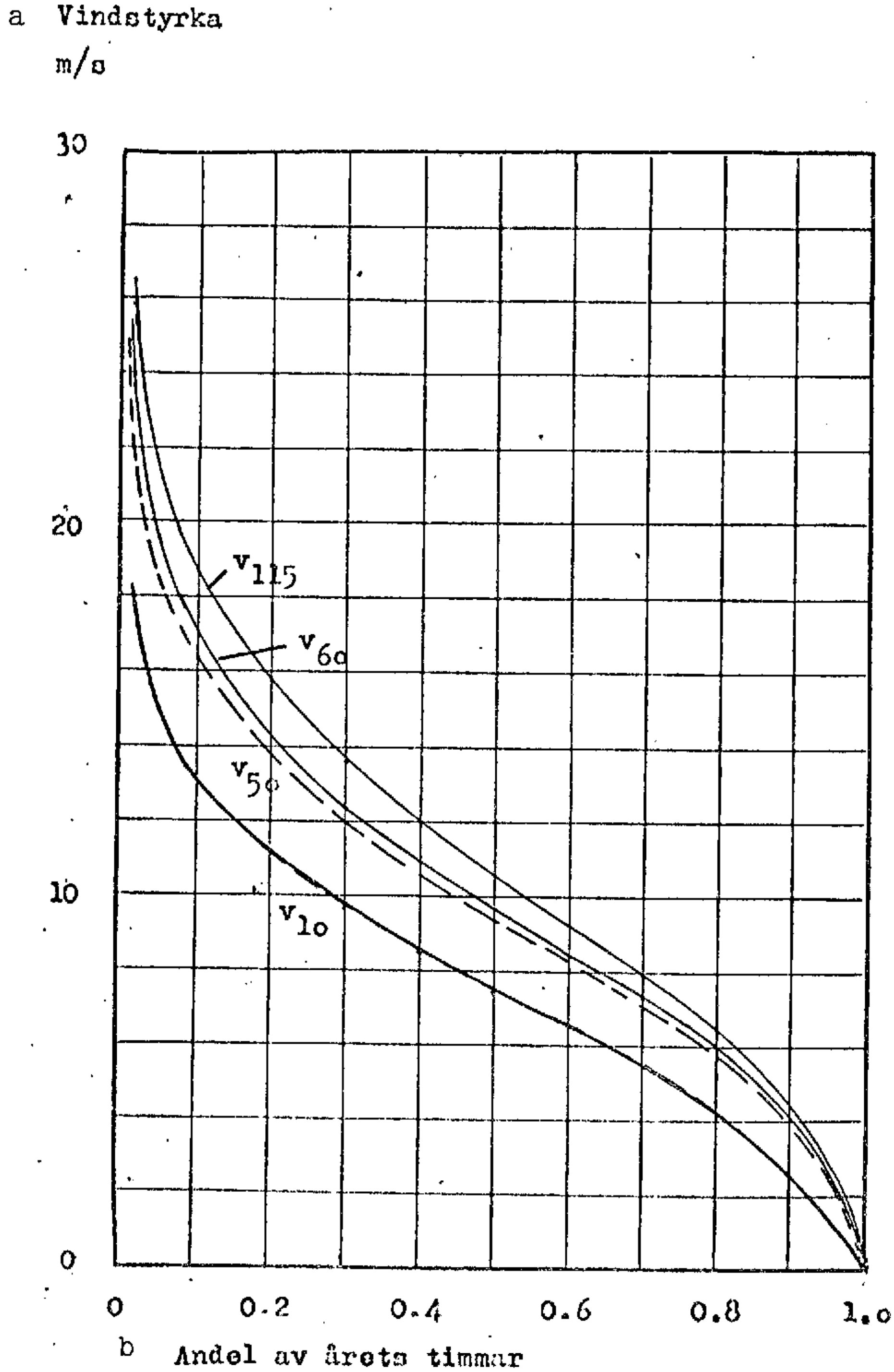


Diagram 8. The wind duration at heights of 10, 60 and 115 m after revising reference data for wind duration at a height of 50 m. See Diagram 2.

Key: a. Wind velocity
b. Year-hours

and 1450 W/m^2. The wind velocities are thus carefully calculated:

$$v_{60} = 12.84 \cdot 2^{1/3} = 16.18 \text{ m/s}$$
$$v_{115} = 14.07 \cdot 2^{1/3} = 17.70 \text{ m/s}$$

The horizontal power limits are noted as $(P_e/A)_{max}$. Together with the lines for P_e/A and the coordinate axis, an area is enclosed which is proportional to the production of electrical energy for 1 year. The unit of area is W/m^2. The yearly energy is

E_{year} = (Area's measurement number) · (propeller area) · (No. of hours yearly)

$$E_{year} = y \cdot A \cdot 8760 \text{ Wh}$$

or $$E_{year} = y \cdot A \cdot 8760/10^6 \text{ MWh}$$

The areas in Diagram 9 (p. 32) are 375 W/m^2 and 497 W/m^2, respectively. A continuation of the lines for $(P_e/A)_{max}$ forms, together with the coordinate axis and the vertical line for the duration, 1.0 rectangles. The relationship between the above-mentioned areas and the rectangles is the mean power density during the year. In the table below are found energy data for the two wind-power machines. /29

Size	Power Limit MWe	Maximum Power Density W/m^2	Diagram Area W/m^2	Rectangle Area W/m^2	Propeller Area m^2	Yearly Energy MWh	Average Power %
$P_{10/10}$=1 MW	2	1106	375	1106	1810	5970	34
$P_{10/10}$=10 MW	20	1450	497	1450	13,800	60,100	34

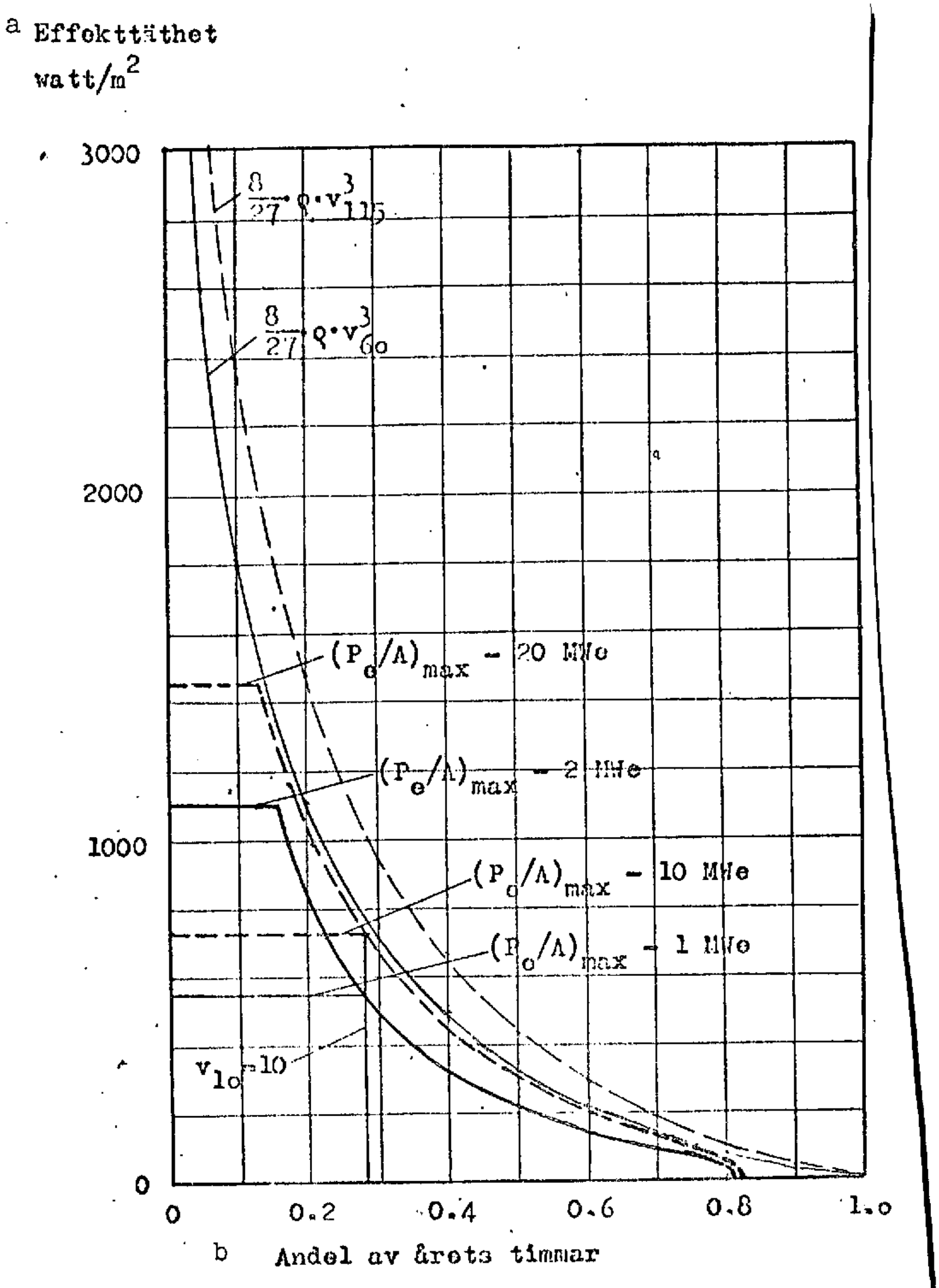


Diagram 9. Duration of power density. Two wind-power machines with $P_{10/10}$ = 1 MWe and $P_{10/10}$ = 10 MWe.

Key: a. Power density
b. Year-hours

Cc. Approximate Calculation of Some Data for Wind-Power Machines /30

Speed at Blade Tip u

The average wind force is greater for a large wind-power machine than for a smaller one, because the propeller axis is located higher above ground. Too great a speed at the blade tip produces a low degree of aerodynamic efficiency at weak wind speed. This also means that at high speed, at the blade tip, the width of the blade could be made smaller and still be sufficient for utilizing all accessible energy in the wind. The following speeds at the blade tip are accepted as suitable:

Propeller diameter 2R, m	130	45	30
Velocity at blade tip u, m/s	90	80	70

This is the speed at the blade tip at a fixed propeller rpm. If a direct-current generator is used, then it is permissible to have a smaller rpm at low wind speed and greater rpm at high wind speed.

Propeller Axis rpm, n

The propeller axis has an angular velocity Ω radians/sed. The relation to the speed at the blade tip is $u = \Omega R$. The relation between rpm (n turns/sec) and angular velocity is $\Omega = 2\pi n$.

Total Propeller Blade Width

A cross-sectional representation of the propeller blades is of a radius $r_{75} = 0.75R$. In order to calculate the approximately necessary width of the blade sufficient to take advantage of available energy at wind velocity v, the following equation is used:

$$\text{Necessary blade width } ib = 7.5 \cdot \frac{R}{c_z} \cdot \left(\frac{v}{u}\right)^2$$

The number of blades is chosen so that b becomes about 10% of R. A lower value of b raises the degree of aerodynamic efficiency, but lessens the solidity. A suitable value of the lift coefficient is c_z = 0.65. The width of the propeller blade should increase toward the center, approximately according to the function $b(r/R)^2$ = constant. According to this function, one calculates the width, e.g., r = 0.35R; in other words, the width should be $(75/35)^2$ = 2.1 times bigger than at a radius of 75%. The blade contour is, as a rule, trapezoidal. The demand of width toward the center is difficult to satisfy. A circular cross section of the attachment of the blade base to the propeller hub is obtained.

Cd. Data Summary. Two Wind-Power Machines $P_{10/10}$ = 1 MW and $P_{10/10}$ = 10 MW /31

Size	$P_{10/10}$ = 1 MW	$P_{10/10}$ = 10 MW
Propeller diameter, 2R, m	48	132.5
Propeller shaft, height above ground	60	115
Propeller blade tip, orbital velocity	80	90
Propeller axis rpm, turns/sec	0.53	0.22
radians/sec	3.34	1.36
Electrical generator rpm, turns/sec	12.5	6.25
Propeller gear, gear ratio	24 = 4.9	28 = 5.3^2
Number of propeller blades	3	2
Each blade width, m, with r = 0.75R	2.4	6
Width sufficient for full energy use, up to v =	13 m/s	14 m/s
Blade-width/blade-length ratio, approx.	1/9	1/11
Axial power in the propeller axis kN (kilonewtons) at wind velocity v = 13 m/s	165	--
v = 14 m/s	--	1530

Wind-power machine's total efficiency between power limits 15 and 50% of maximum power	0.7	0.7
Maximum electrical power, MW	2	20
Electrical power at wind velocity		
v = 12.8 m/s	1	--
v = 14.1 m/s	--	10
Estimated energy production in 1 year, MWh	5970	60,100
Mean power/maximum power ratio in a year	34%	34%
Energy production calculated from duration curve with starting point for wind speed at propeller height, mean value for the year, v in m/s =	9.5	10.7

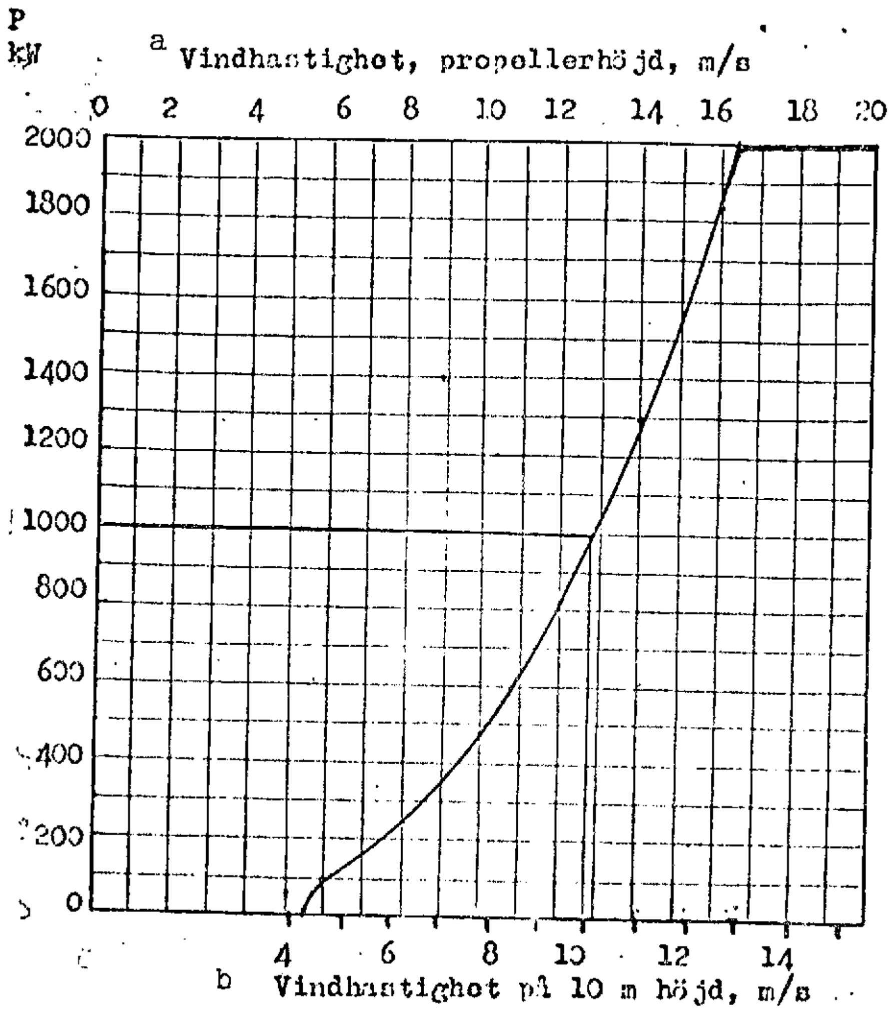


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Diagram 10. Wind-power machine with 2 MW maximum electrical power. The power as a function of wind velocity. The power at wind velocity v at propeller height is:

$$P = 0.296 \cdot \eta \cdot \rho \cdot A \cdot v^3 = 0.296 \cdot 0.70 \cdot 1.26 \cdot 1810 \cdot v^3 = 472 \cdot v^3 \text{ watt} = 0.472 \cdot v^3 \text{ kW}$$

Wind velocity at a height of 10 m is:

$$v_{10} = v \cdot (10/60)^{0.14} = 0.778 \cdot v$$

Key: a. Wind velocity, propeller height
b. Wind velocity at height of 10 m

K. Energy Costs: Use of Electrical Energy for Heating Apartment Houses and for Other Heating Purposes, Plus the Concomitant Energy Accumulation /33

Construction of a wind power plant costs 1000 kr/kW, with series-manufacture of the machines. Yearly production of electrical energy amounts to 5000 kWh/kW. If cost of capital and operation is assumed to be 15% per year of the construction cost, then the original cost price for electrical power becomes 150/5000 = 0.03 kr/kWh for energy delivered directly from the wind-power plant.

The construction cost of a power plant is estimated at 1000 kr/kW. In order for wind power plants, together with other types of power plants, to be able to deliver satisfactory energy, the power plant ought to extend its power to about 70% use of wind power. Then the total construction cost would be 1700 kr/kW. Because of transmission loss and losses in the power plant's pumps and turbines, the above-mentioned figure of 5000 kWh/kW is reduced to 4600 kWh/kW. The price of energy for the total construction (wind power plus pump power) then becomes 0.15 x 1700/ /4600 = 0.055 kr/kWh.

If electrical power is to be used for heating purposes as an alternative to crude oil, it must be competitive in price with oil. The price of crude oil today is about 15 kr/Gcal (1 Gcal - 1163 kWh). Burning efficiency = 90%. The price of heat is then 1.4 ore/kWh. Wind-generated electrical energy, excluding the cost of energy storage, costs 3 ore/kWh, according to the above data. It is then economically unsound to build wind power plants to compete with crude oil for heating purposes. Only underselling of surpluses would make sense. If the price of crude oil were about 35 kr/Gcal, wind power plants would be feasible.

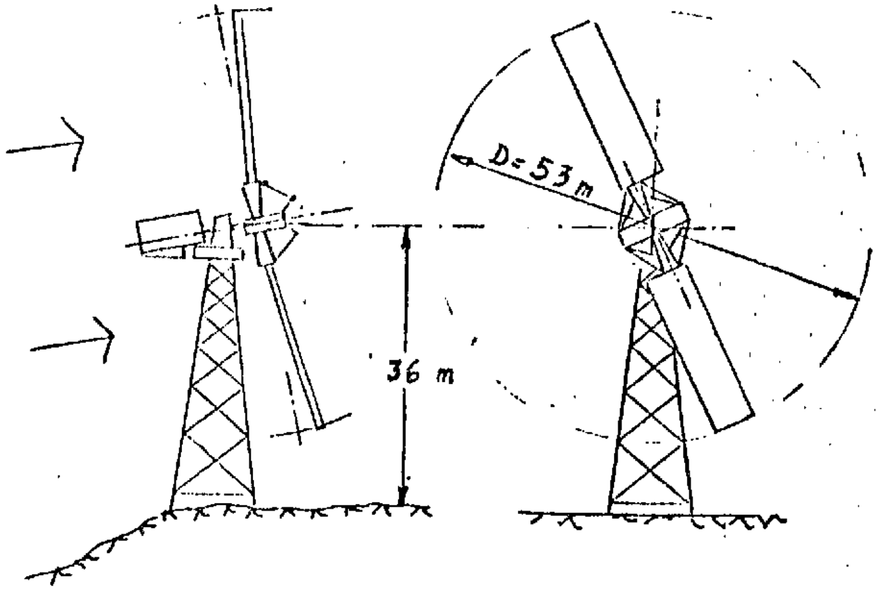
If electrical energy is used for single-residence heating, the competition would be with refined oil, at a price of about 400 kr/m^3. The density of refined oil is 895 kg/m^3, making the price 45 ore/kg. The heat of burning is 42 MWs/kg = 11.7 kWh/kg. Burning efficiency is 80%. The cost of heating with refined oil then becomes 4.8 ore/kWh. It is possible, however, to arrange low-cost heating with electrical energy for single residences by using energy only at night, thereby reducing the need to regulate the electrical power on a 24-hour basis; however, one must regulate wind power in periods of weeks. Therefore, one does not save the power plant requirements when regulation on a 24-hour basis lessens or disappears. In regard to a power plant, one can also regulate a low additional amount per 24-hour period. It is therefore not feasible to use wind-generated electrical energy for single-family residences, according to this calculation.

Wind-Power Machines Tested

Year pilot operation begun	1941 Grandpa's Knob, Vermont, USA	1953 St.Albans, Dorset, Great Britain	1957 Stötten, Swabian Alps, FRG	1957 Gedser, Falster, Denmark
Propeller diameter, m	53	24	34	24
Propeller area, m^2	2220	450	910	450
Number of propeller blades	2	2	2	3
Propeller blade tip orbital velocity, m/s	80	120	75	39
Propeller rpm	29	95	42	30
Electrical generator power, kW	1250	100	100	200
Power density, W/m^2	560	220	110	445
Full power at wind velocity (m/s)	15.3	14	8	15

Total efficiency, %	44	22	63	35
Generator begins to give power at wind velocity (m/s)	7.6			5
Yearly mean value for wind velocity at test site, approx. (m/s)	7.5	6		6
Tower height, m	36	30	22	24
Tower height/propeller diameter	0.68	1.25	0.65	1.0
Type of electrical generator	synch.	synch.	synch.	asynch.
Generator rpm	600			750
Transmission type	gear drive	pneum.	gear drive	chain
Transmission gear changes	21			25
Blade angle regulator	Entire blade	Entire blade	Entire blade	Blade tip
Blade angle servo	hydraul.	hydraul.	hydraul.	pneum.
Propeller position relative to tower	lee	lee	lee	wind
Wind direction servo	electr.	electr.		electr.

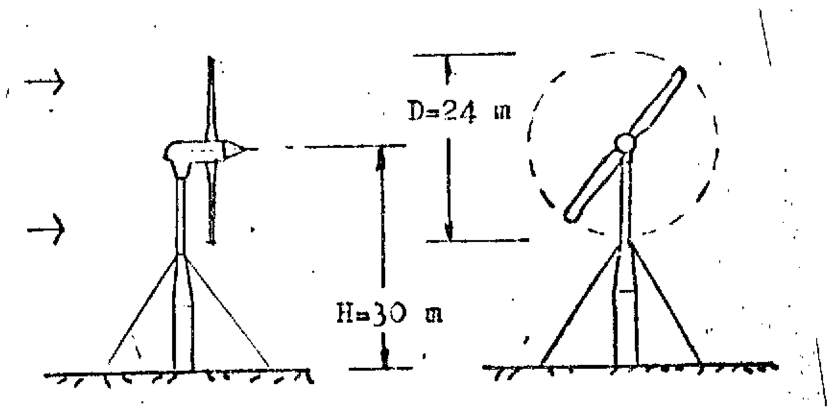
GRANDPA'S KNOB 1941-1945



Main data	Propeller diameter 53 m. Tower height 36 m. Generator power 1250 kW. Propeller area 2220 m^2. Power density 560 W/m^2.
Propeller	Two blades. Uniform blades between 25-100% radius, not paddle-shaped. Supporting shell of stainless steel, reinforced by crossbars and girders. Hydraulic blade angle adjustment. Mechanism that allows the blades to yield to the wind's "cone," by which bending is lessened. 28.7 rpm. Blade tip speed 80 m/s.
Generator	AC synchronous machine with additional magn. gen. 1250 kW, 600 rpm
Full power at wind velocity	15.3 m/s
Total efficiency	Theoretical power at 15.3 m/s is 2840 kW. Total efficiency 1250/2840 = 0.44.

Transmission	Gear. 21 gear changes. Hydraulic coupling to limit moment at axis to generator
Wind direction	Propeller on tower lee side. Gear ring on tower top and adjustable electrical motor steered by weathervane.
Tower	Steel construction. Height 36 m.
Financing	S. Morgan Smith Company, USA
Construction Manager	P.C. Putnam
Test operation	Constructed at Grandpa's Knob, Vermont, USA. Test-operated and mounted in the network during 1941-1945. Further testing discontinued after propeller broke in March 1945.
Source of Information	Ref. 5.

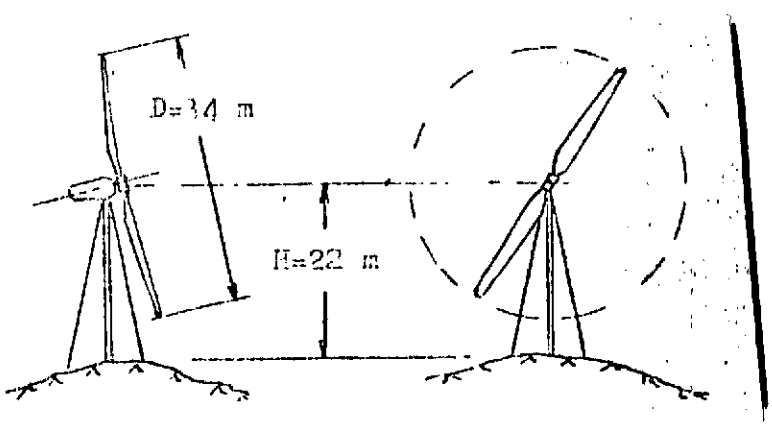
Enfield-Andreau at St. Albans. Testing begun in 1953.



Main data	Propeller diameter 24 m. Tower height 30 m. Generator power 100 kW. Propeller area 450 m^2. Power density 220 W/m^2.
Propeller	Two blade. Self-supporting steel shell with smooth interior. Blade angle regulator with hydraulic servo. The blades can also change angle relative to the axis of the "cone." Blade tip speed variable, maximum 120 m/s, at which there are 95 rpm.
Wind velocity at full power	14 m/s

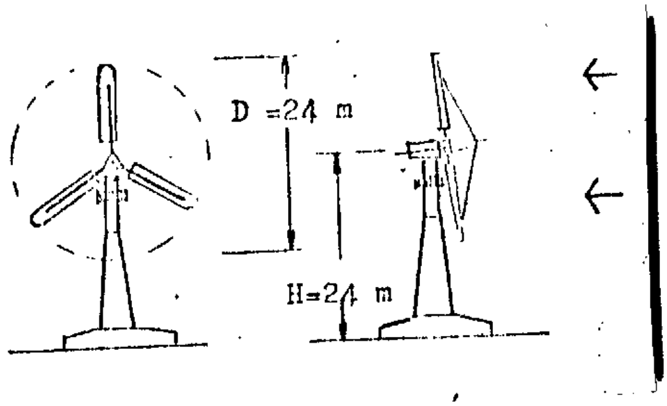
Total efficiency	Theoretical power at 14 m/s is 450 kW. Total efficiency 100/450 = 0.22.
Generator	AC synchronous machine
Transmission	The air is thrown by centrifugal force through holes in the propeller blade's outer tips and is sucked through the propeller blade and tower pipe. At the bottom of this is an air turbine, which drives the generator. Turbine and generator have the same revolution speed and are directly connected, with no intermediate gear.
Wind direction	The propeller is on the tower lee side; it is self-adjusting with the aid of a servo.
Tower	Steel pipe, overhung at the top, braced in the middle with steel cables to the ground. The wider, lower section contains turbine and generator with vertical axis.
Financing	British Electricity Authority
Construction, Manufacturer	Enfield Cables, Ltd., after an invention by the Frenchman J. Andreau. A small attempt at construction was tried in France.
Test Operation	Test operation started at St. Albans, Dorset, 1953
Source of Information	Refs. 4 and 11

Stötten near Geislingen, Swabian Alps. Testing begun in 1957.



Main data	Propeller diameter 34 m. Tower height 22 m. Generator power 100 kW. Propeller area 910 m^2. Power density 110 W/m^2.
Wind velocity at full power	8 m/s
Total efficiency	Theoretical power at 8 m/s is 158 kW. Total efficiency 100/158 = 0.63.
Propeller	Two blades. Fiberglass-reinforced plastic blade with supporting shell. Designed for high aerodynamic efficiency. Hydraulic blade angle adjustment. 42 rpm. Blade speed 75 m/s
Generator	AC synchronous generator, 100 kW
Transmission	Gear
Wind direction	Propeller on tower lee side
Tower	Thin-walled steel pipe about 1 m in diameter. Three steel support cables between top of mast and ground.
Financing	Studiengesellschaft Windkraft
Construction manager	Prof. U. Hütter, Chairman, Aviation Department, Institute of Technology, Stuttgart
Test Operation	Testing begun at Stötten in 1957. A year later the machine was furnished with equipment for automatic mounting in the network
Source of Information	Ref. 10

Gedser, on the island of Falster, Denmark. Testing begun in 1957.



Main data	Propeller diameter 24 m. Tower height 24 m. Generator power 200 kW. Propeller area 450 m^2. Power density 445 W/m^2 of propeller area.
Wind velocity at full power	15 m/s
Total efficiency	Theoretical power at 15 m/s is 566 kW. Total efficiency 200/566 = 0.35.
Propeller	Three blades. Uniform paddle-shaped blades between 25 and 100% radius. Supporting steel box girder. Wood crossbars. 1-mm aluminum shell. The blades are anchored by side supports from a prominent point of the hub. The outer portion of blades is made to turn via the axis to the center of hub and blade angle servo. 30 rpm. Blade tip speed 39 m/s.
Generator	AC asynchronous machine. 200 kW. 3 x 380 V. 750 rpm.
Transmission	Double chain. 25 exchanges
Wind direction	Propeller on tower wind side. Gear ring on tower top and electric motor. Steering by weathervane.
Tower	Thick pipe of reinforced concrete on heavy tripodal concrete foundation.
Financing	Association of Danish Electricity Works (Danske Elvearkers Forening = DEF)

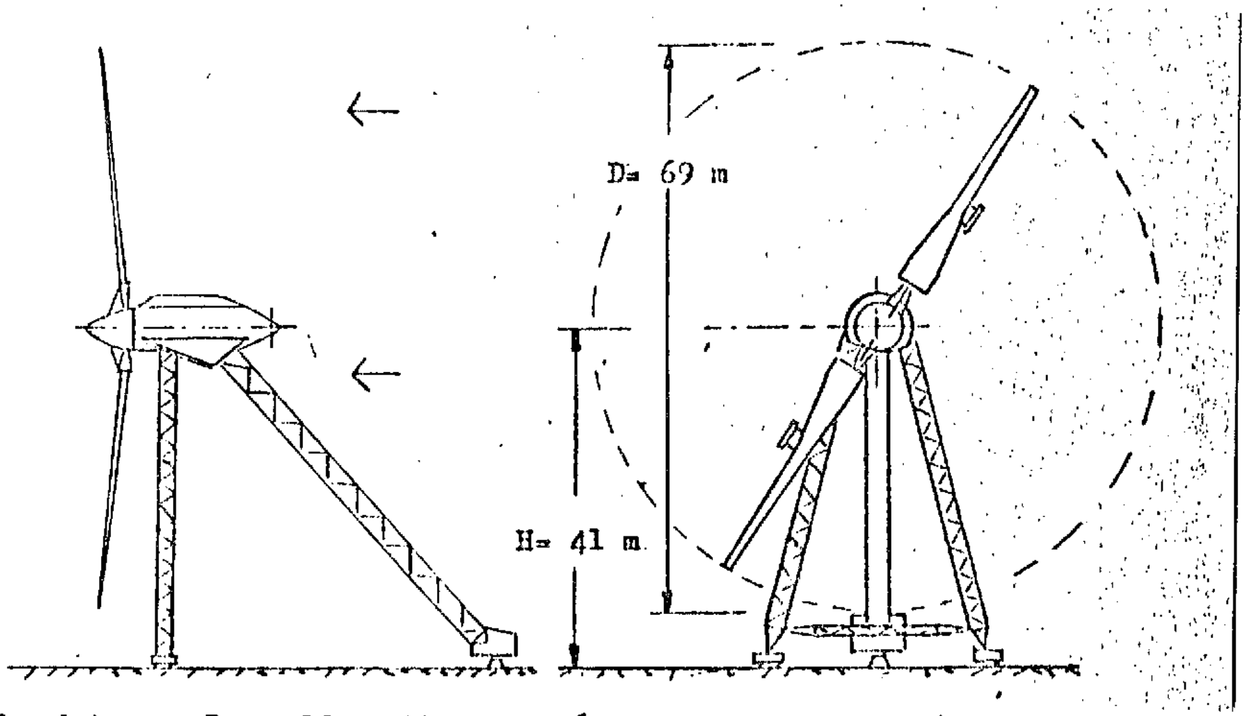
Project manager	J. Juul
Test operation	Begun summer 1957. Testing continued during the following year. Electrical energy delivered to SEAS power network (SEAS = Sydostsjällands Elektricitets Aktiesellskab)
Source of Information	Refs. 10 and 14.

Wind-power machines, Project. Technical data:

Proposed by	P.H. Thomas	Folland Aircraft	Olle Ljungström	Olle Ljungström	Bengt Södergård
Year projected	1946	1951	1974	1974	1973
Propeller diameter, m	61	69	150	50	32
Propeller area, m^2	5900	3750	17,700	1970	800
Number of propeller blades	3	2	2	2	3
Propeller blade tip orbital velocity, m/s	168	153	varies: max. 80	varies: max. 70	varies: max. 75
Propeller rpm	52	42	max. 10	max. 27	max. 45
Electrical generator power, kW	7500	3760	20,000	2000	200
Power density, W/m^2	1270	1000	1070	1000	250
Full power at wind velocity, m/s	17	15.6	13.1	12.2	9.7
Total efficiency, %	70	72	66	66	72
Generator begins giving power at wind velocity, m/s					4.2
Tower height, m	145	41	108	56	40
Tower height/propeller diameter	2.4	0.6	0.7	1.1	1.3

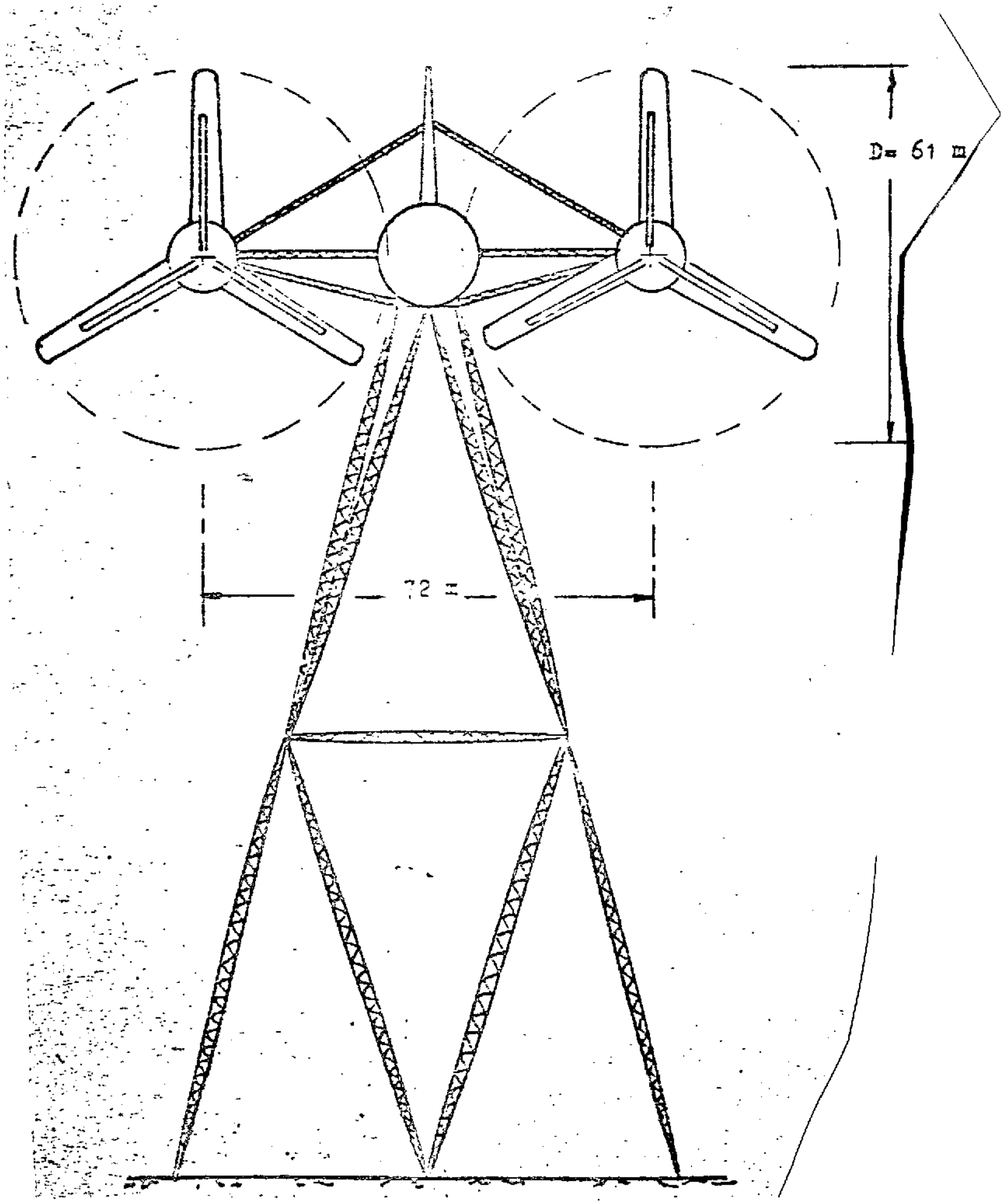
Electrical generator, type	dc	asynch.			dc
Generator rpm	variable, max.		375	1000	variable, max. 1000
Transmission type	gear	gear	secondary propeller	secondary propeller	gear
Blade angle regulation	lacking	whole blade	aerodynamic brakes in blade tip		whole blade
Blade angle servo	lacking	aerodyn. slotted wing			electr.
Propeller position relative to tower	wind	lee	wind	wind	lee
Adjustable motor for wind direction, type	electrical	not necessary	electrical	electrical	lacking

Folland Aircraft, Ltd. project. Great Britain, 1951.



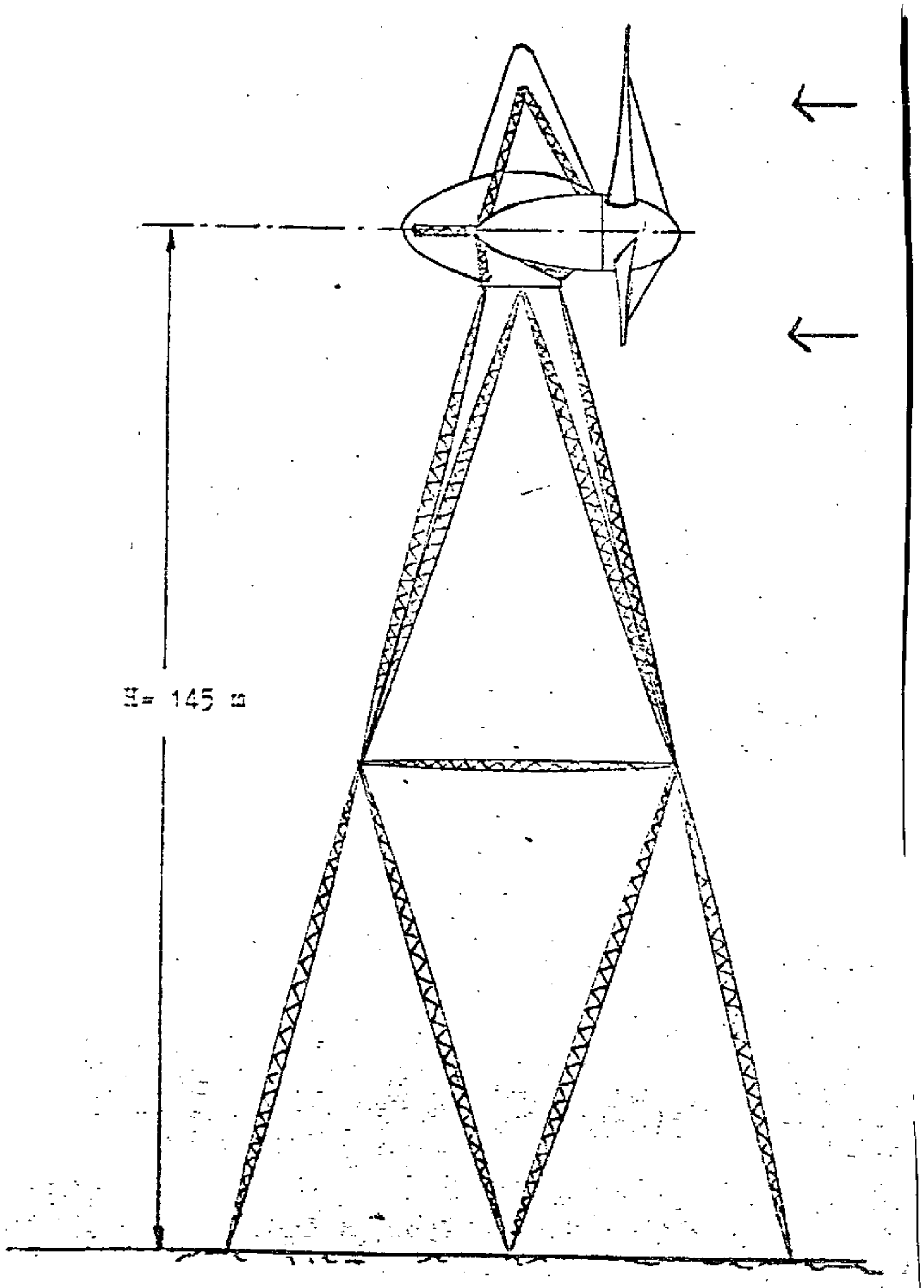
Main data	Propeller diameter 69 m. Tower height 41 m. Generator power 3760 kW. Propeller area 3750 m^2. Power density 1000 W/m^2.
Wind velocity at full power	15.6 m/s
Total efficiency	Theoretical power at 15.6 m/s is 5200 kW. Total efficiency 3760/5200 = 0.72
Propeller	Two blades. The blades can be turned and yield to the wind's "cone." Turning of the propeller blades is accomplished by slotted wings behind the propeller side. These slotted wings are guided by a servo. 42 rpm. Speed at blade tip 153 m/s.
Generator	AC asynchronous machine.
Transmission	Two-step gear in quick exchange with propeller axis and generator axis
Wind direction	Propeller on tower lee side. The wind forces turn the tripod in the direction of the wind. For this turning, the chassis is also the drive mechanism.

Tower	Tripod construction in steel. One strong, angled leg is able to turn around a center plate anchored in the ground. The other two legs rest on the chassis which runs on circular rails on the ground.
Commission given by	Ministry of Fuel and Power
Projection	Folland Aircraft, Ltd., Great Britain
Source of Information	Ref. 4



Project by P.H. Thomas, USA, 1946.

[Continued on following page.]


H= 145 m

REFERENCES

1. Ångström, A., Sveriges klimat [The climate of Sweden], Generalstabens litografiska anstalts Press, Stockholm, 1958, 155 pp. + plates.

2. Sutton, O.G., Atmospheric turbulence, 2nd ed., Methuen & Co., Ltd., London, 1955 (reprinted 1960), 111 pp.

3. Byzova, N.L., Investigation of the bottom 300-meter layer of the atmosphere, USSR Academy of Sciences, Translated and printed in Israel, Jerusalem, 1965, 112 pp.

4. Golding, E.W., The generation of electricity by wind power, E. & F.N. Spon, Ltd., London, 1955, 300 pp.

5. Putnam, P.C., Power from the wind, D. Van Nostrand Co., Inc., New York, 1948, 224 pp.

6. Thorslund, B., Och nu vädret ... [And now the weather ...], Swedish Radio Press, Stockholm, 1970, 64 pp.

7. Prandtl, L., Führer durch die Strömungslehre [Guide to flow mechanics], Friedr. Vieweg & Sohn, Braunschweig, 1960, 407 pp.

8. Hütte, from Ingenieurs Taschenbuch, Maschinenbau [Engineer's handbook, machine-building], 28th ed., Verlag von Wilhelm Ernst & Sohn, Berlin, 1954.

9. Hult, J., T. Widell et al., Ingenjörshandboken, tekniska grundvetenskaper [Engineer's handbook, technical and scientific principles], Nordisk Rotogravyr, Stockholm, 1966, 1269 pp.

10. Clausnizer, G.,"Wind power," Brennstoff-Wärme-Kraft 14/7, 321-326 (July 5, 1962).

11. Golding, E.W., "Electrical energy from the wind," The Inst. of Electr. Eng., Paper S 1727 (1954).

12. Golding, E.W., "Electricity from wind power," British Power Engineering, 33-35 (Sept. 1960).

13. "Electricity supply in Sweden 1975-1980," 1972 study, CDL report.